

Modelling of a Wall Inlet in Numerical Simulation of Airflow in Livestock Buildings

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ABSTRACT

The aim of this work is to develop applicable methods to model wall inlets in numerical simulations of airflow in livestock buildings.

Simulations were compared with measurements in an 8.5 m long, 3 m high and 10.14 m wide test room. A prefabricated wall inlet was centred 0.50 m beneath the ceiling and 5.87 m from one side wall of the room. The inlet was adjusted to supply 0.1 m³/s at a pressure difference of 10 Pa.

Close to the inlet, air speed was significantly below the one predicted with a coarse orthogonal grid. Grid refinement in high velocity areas improved the agreement with measurements close to the inlet. But repeating refinements increased the number of cells so much, that the computer capacity limited the use of this technique.

The construction of grids with cells orientated parallel to the inlet direction was more time consuming, but made it possible to obtain a fairly good agreement with measurements using relatively few cells. A complete geometric modelling of the inlet was even more time consuming, but increased the agreement with measurements and eliminated the need of measuring data to specify the inlet direction. Including the volume in front of the inlet gave small changes in the airflow pattern inside the room even though calm air flow conditions were assumed in front of the inlet.

Keywords: CFD, Wall inlet, Airflow, Livestock rooms, Numerical simulation, Measurements

INTRODUCTION

The aim of this work is to develop applicable methods to model wall inlets in numerical simulations of airflow in livestock buildings. Earlier work on the development of numerical simulation methods to predict airflow in livestock buildings have focused

on the influence of room geometry and heat production from the animals, see eg Bjerg et al. (1999) and Zhang et al. (1999). To predict the airflow in practical husbandry, it is necessary to obtain more knowledge on the significance of air inlets. Mechanical ventilation systems in pig and poultry houses are often equipped with prefabricated wall inlets with automatically controlled openings, see figure 1.

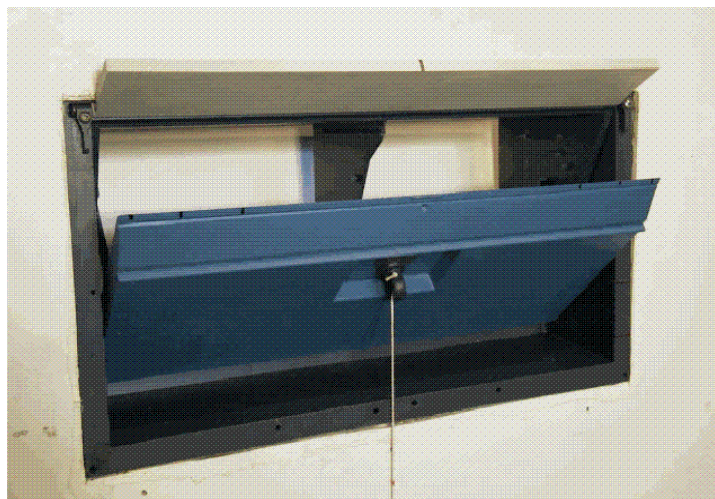


Fig. 1. Prefabricated wall inlet (Skov 1200). The bottom-hinged flap is usually controlled by an automatic control system. The top hinged flap is manually controlled to obtain a suitable inlet angle.

Wall inlets are usually adjusted and controlled to lead the incoming air into the room in an upward direction. The airflow follows the ceiling for some distance from the inlet. From there it continues as a wall jet unless a possible heat load or a geometric obstacle causes it to drop from the ceiling.

From a pragmatic point of view the purpose of using numerical simulations in livestock rooms is to predict climate conditions in the occupied zone. Consequently, methods to model inlet conditions have to be good enough to ensure that they will not be a reason for significant miscalculations of the conditions in the occupied zone. Therefore, in this work we evaluate different methods to model an inlet based on the degree of agreement with air velocity measurements in the occupied zone.

A general introduction to the application of numerical simulation in ventilated rooms is given by Awbi (1989). Earlier studies on airflow in livestock rooms have used uncomplicated openings located close to the ceiling, and the air entered the rooms as wall jet (eg Bjerg et al. 1999; Bjerg et al. 2000; Svidt 1994). In these arrangements it is natural to use hexagonal grids where the jet is parallel to grid. But hence the air inlet is not parallel to the room surfaces in this study the grid constructions requires more considerations. Diagonal airflow in the cells can cause increased numerical diffusion, which can be a serious source of error in numerical simulations (see eg Anonymous 1998).

A finer grid resolution will reduce the numerical diffusion but will at the same time require more computer memory and increase the calculation time. A reduction of numerical diffusion might also be obtained by changing the numerical discretization scheme.

In this investigation two types of hexagonal grids were compared – orthogonal grids and grids where the cells were orientated parallel to the inlet. Orthogonal grids are easy to construct but imply the mentioned risk of miscalculations caused by numerical diffusion. In an attempt to reduce this risk, simulations were made with local refined grids and the First-Order Upwind Scheme (default in the used simulation code) was replaced with the Second-Order Upwind Scheme (see Anonymous 1998).

In uncomplicated inlets it is natural to specify the inlet boundary condition in the plane where the jet is entering the room. But the complex geometry of the inlet used in this study makes it difficult to determine in which plane or planes the jet enters the room, and in addition it is difficult to obtain information on such boundary condition by measurement. Therefore, the inlet was modelled either as a simple rectangular opening, or as a geometric model of the entire inlet or even of a volume in front of the inlet. Assuming a rectangular opening implies estimations of the opening properties but the geometric modelling is easy to carry out. A complete geometric modelling of the inlet is more complicated, but on the other hand it is easy to specify inlet condition by distributing the entire airflow over a well defined area.

Earlier work (Bjerg et al. 2000) shows that the introduction of temperature differences between inlet air and room air increase the uncertainty in numerical prediction of the airflow pattern in the used test room. This work is focussed on inlet modelling and to reduce uncertainties from other circumstances the investigation is carried out at isothermal conditions.

MATERIAL AND METHODS

Measurements

Measurements were carried out in an 8.5 m long, 3 m high and 10.14 m wide test room. The prefabricated inlet type DA 1200 (figure 1) from the Danish ventilation company SKOV was 0.54 m wide and centred 0.50 m beneath the ceiling and 5.87 m from one side wall of the room. The inlet was adjusted to supply 0.1 m³/s at a pressure difference of 10 Pa. The geometry of the inlet condition is shown in figure 2.

The air was exhausted from the room by a slot in the floor close to the inlet wall. Figure 3 shows the room geometry, the measuring points and the used system of co-ordinates. Beneath the ceiling airspeed was measured with a thermistor based omnidirectional airspeed sensor system developed at the Danish Institute of Agriculture Science, Research Centre Bygholm. The accuracy of the used sensors were better than 2 % in the range from 0.3 to 10 m/s (Zhang *et al*, 1996) and the sensor system was used to determine vertical air speed profiles in the symmetrical plane of the inlet at x=0.5 m, x=1.5 m and x=4.5 m. The y-coordinate of the highest measured air speed at x=0.5 m was used to determine the inlet direction. Horizontal profiles were measured at x=0.5 m,

$x=1.5$ m and $x=4.5$ m at the height where the highest air speed was measured in the vertical profiles. An ultrasonic air velocity sensor (Windmaster, Gill instruments, England) was used to determine air velocity 0.20 m above the floor. The x- and z-coordinates of the ultrasonic measuring point appear from figure 3. The accuracy ultrasonic sensor was 1.5 % with a resolution of 0.01 m/s and an offset of 0.01 m/s. Reported air speed and air velocities are time average values of 25 minutes of measurement.

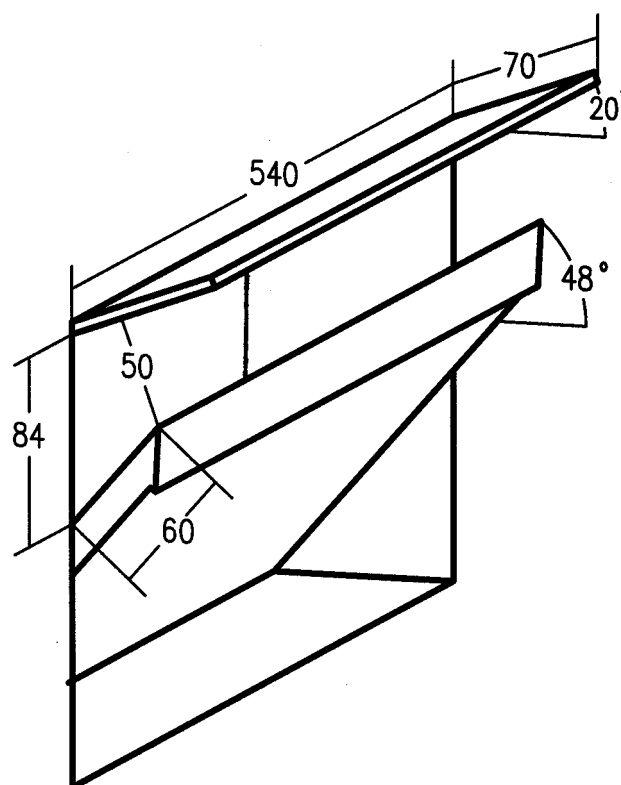


Fig. 2. Geometry of inlet conditions.
Dimensions in millimetres, angles in degrees.

Simulations

Airflow was predicted by the commercial numerical simulation code Fluent 5 (Fluent Inc). The K- ϵ turbulence model (Launder and Spalding, 1974) and a pressure outlet boundary condition was used in all simulations in this work. Simulations were made with both first- and second-order upwind discretization scheme (see Anonymous 1998).

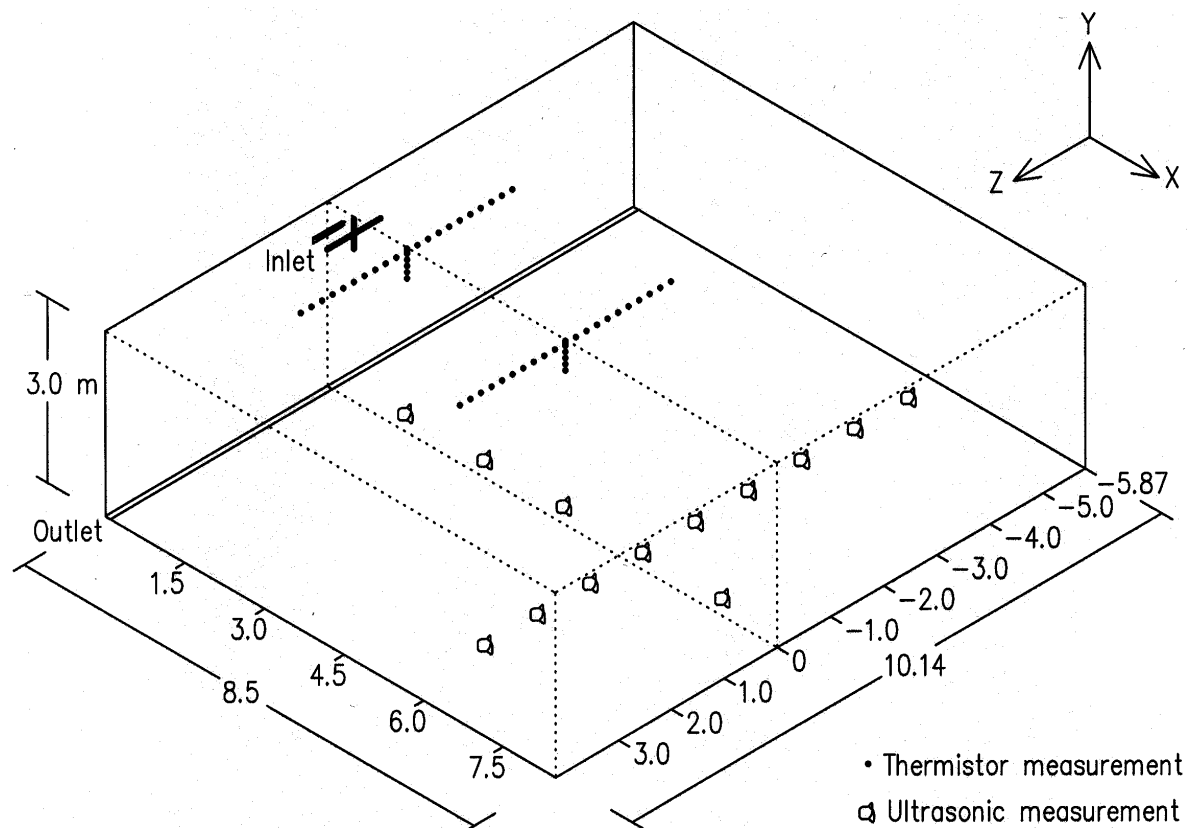


Fig. 3. Geometry of room and location of measuring points. Thermistor sensors were used in the jet and a ultrasonic sensor was used in measurements 0.2 m above floor. Dimensions in metres.

Inlet conditions

The inlet condition was modelled in three different ways – as a simple orthogonal opening, as a geometrical model of the inlet including flap and guiding plate, and as a geometrical model of the inlet including flap, guiding plate and air volume in front of the inlet (see figure 4).

Use of a simple orthogonal opening requires information on inlet velocity, inlet direction and inlet area. Air speed measurements at $x=0.5$ m showed that the inlet direction was 25 degrees upward. The complex geometry of the inlet made it impossible to measure the opening area in a suitable way and, therefore, the inlet velocity was determined from the pressure drop equation (Andersen 1996):

$$\Delta p = \frac{1}{2} \rho v_c^2 (1 + \zeta)$$

where Δp is the pressure drop, Pa, ρ is density of air, kg/m^3 , v_c is the mean air velocity in the vena contracta (the cross section where the air speed is maximum, see Andersen 1996), and ζ is the resistance coefficient. Assuming a pressure drop of 10 Pa and a

resistance coefficient of zero the inlet velocity was estimated to 4.1 m/s. Assuming an inlet direction of 25 degrees, the horizontal velocity component was 3.7 m/s and the vertical velocity component was 1.8 m/s. The inlet area (0.027 m^2) was estimated from the airflow rate ($0.1 \text{ m}^3/\text{s}$) and the horizontal velocity component. The inlet used in the simulations was 0.05 m high, 0.54 m long and its centre was located 0.5 m beneath the ceiling. For a corresponding opening Andersen states a resistance coefficient of 0.1. The consequences of using this value would be that the calculated inlet air speed would be about 5 % smaller, the inlet area would be 5 % larger and the anticipated airspeed in the room would decrease with about 2%.

In the geometric models (figure 4 C and D) the inlet boundary was moved to places where the airflow could be easily distributed to a well-defined area.

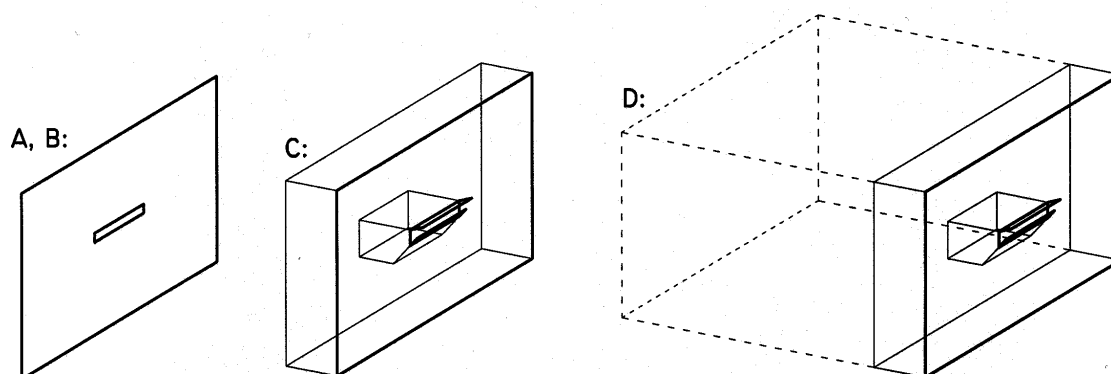


Fig. 4. Inlet models: A, B: Simple orthogonal opening. C: Geometrical model including flap and guiding plate. D: Geometrical model including flap, guiding plate and air volume in front of the inlet.

Grid distribution

Figure 5 and table 1 gives an overview of grid constructions used in the simulations. A simple orthogonal opening is assumed in the orthogonal A-grids and in B-grids where the cells are orientated in the inlet direction.

The code – Fluent 5 – has a grid refinement feature, which was used to create grid A2 by dividing cells where the air velocity in the converged solution from grid A1 was larger than 1.0 m s^{-1} . Cells were divided in all three dimensions and, therefore, one cell became 8 (2^3) new cells. Grid A3 and A4 were created by repeating refinements in the high velocity region, see table 1. From grid A1 to A4 the number of cells increased from 57 456 to 130 697. A further refinement required a larger memory than the one installed on the computer available.

The entire inlet - with flap and guiding plate - was included in grid C1. Grid C2 was created by refinements of cells in the region where air velocity in the converged solutions from grid C1 was larger than 1 m/s. Grid D1 and D2 was created in a corresponding way, but included the airflow in front of the inlet. Outside the inlet region it was aimed to use a uniform cell distribution in all grids. An example of the cell distribution on room surfaces is shown in figure 6.

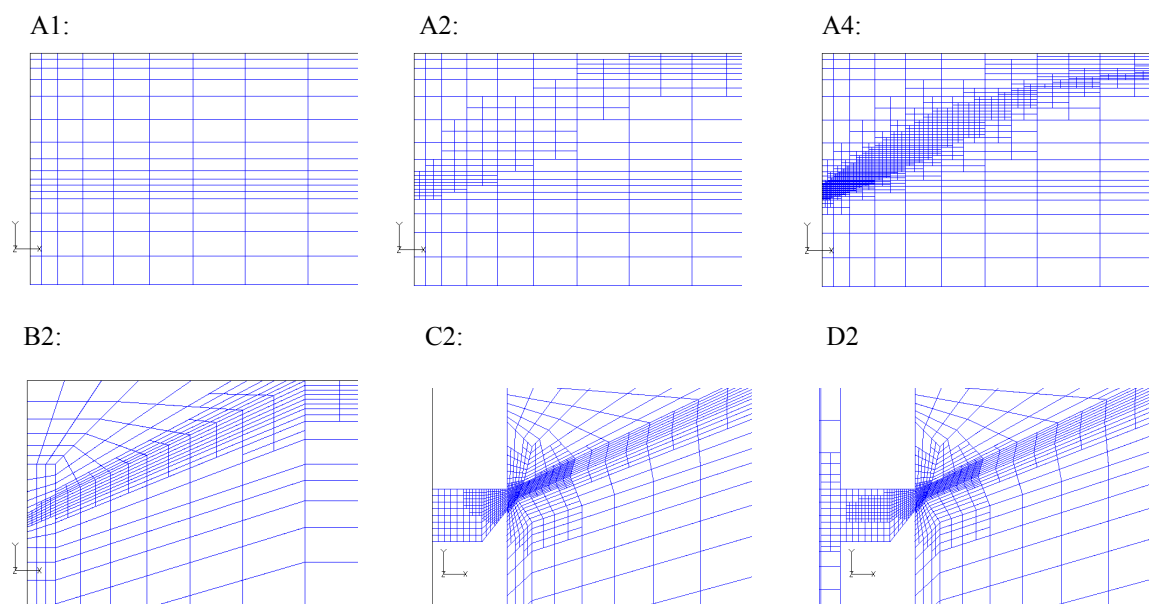


Fig. 5. Grid distribution in the symmetry plane of the inlet. Descriptions of the grids appear from table 1.

Table 1. Overview of simulations and comparison with measurement in a point in the jet 0.5 metre from the inlet ($x,y,z=0.5$ m, 2.74 m, 0 m) and in a point in the occupied zone ($x,y,z= 6$ m, 0.2 m, 0 m). Simulation with first- and second-order upwind discretization schemes.

	Number of cells	$(x,y,z)=(0.5,2.74,0)$		$(x,y,z)=(6,0.2,0)$	
		1. order	2. order	1. order	2. order
Simulations:		Air speed, m/s			
A1: Orthogonal, structured grid , simple opening	57 456	1.18	1.42	0.11	0.15
A2: A1 refined at $v>1$ m/s	59 787	1.52	2.21	0.13	0.19
A3: A2 refined at $v>1.3$ m/s	67 767	1.91	2.6	0.15	0.19
A4: A3 refined at $v>1.5$ m/s	130 697	2.30	2.9	0.16	0.20
B1: grid parallel to inlet, simple opening	49 734	2.70	2.6	0.17	0.20
B2: B1 refined at $v>1$ m/s	55 327	2.93	2.9	0.17	0.20
C1: Grid parallel to inlet, geometric opening	60 628	1.95 ^{*)}	2.2 ^{*)}	0.16	0.19
C2: C1 refined at $v>1$ m/s	86 815	2.78	2.7	0.16	0.19
D1: C1 + volume in front of inlet	62 416	1.95 ^{*)}	2.7	0.16	0.18
D2: C1 refined at $v>1$ m/s	89 023	2.86	2.9	0.16	0.17
Measurement		2.82		0.13	

^{*)} air speed was 2.7 m/s at $y=2.70$ m.

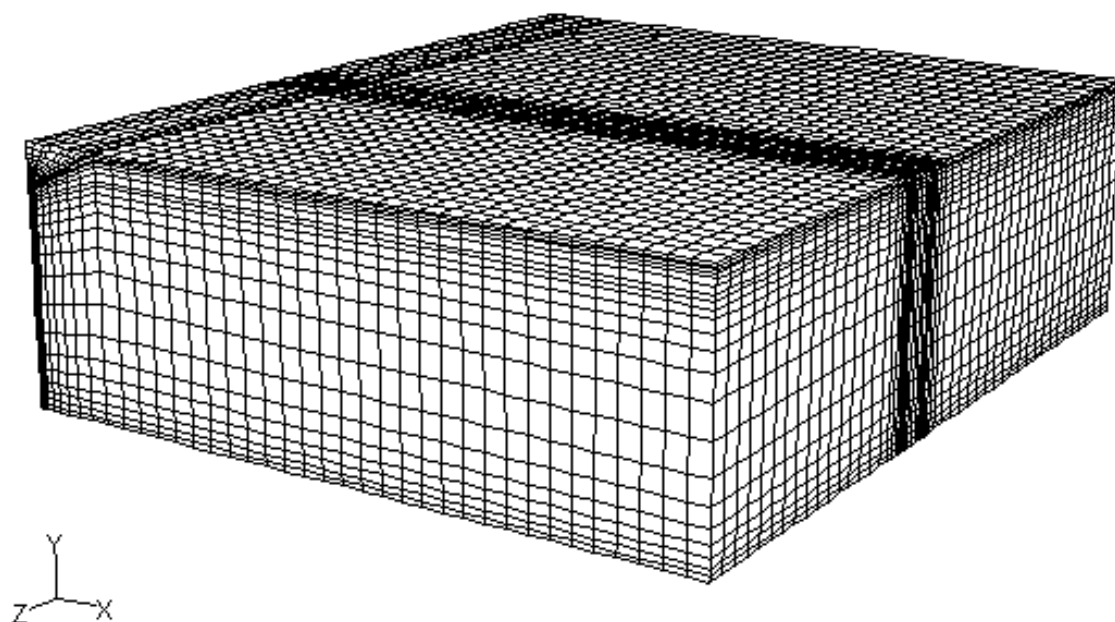


Fig. 6. Grid distribution at room surfaces in simulation B1.

RESULTS AND DISCUSSION

Close to the inlet air speed was significantly under predicted with a coarse orthogonal grid (A1 or A2) (see table 1 and figure 7). Changing to the second-order upwind discretization schemes improved the agreement with measurement but did also reduce the stability of the simulations. Grid refinement in high velocity areas (grid A2, A3 and A4) improved the agreement with measurements close to the inlet. But repeating refinements increased the number of cells so much that the computer capacity limited the use of this technique.

The construction of grids with cells orientated in parallel to the inlet direction (grid B1 and B2) was more time consuming, but made it possible to obtain a fairly good agreement with measurement using relatively few cells. Geometric modelling of the inlet (grid C1 C2) was even more time consuming, but increased the agreement with measurements and eliminated the need of measuring data to specify the inlet direction. Including the volume in front of the inlet (grid D1 and D2) gave small changes in the airflow pattern inside the room, even though calm air flow conditions were assumed in front of the inlet.

Figure 7 ($x=0.5$ m, $y=2.74$ m) shows that the horizontal air speed profiles were asymmetric even close to the inlet. In measurements it is reasonable to explain this skewness by uncertainties in the inlet geometry, but it was surprising that the skewness also was found in the simulations and this indicates that it might be caused by other conditions. Simulation D2 was close to measurement at $x=0.5$ m, whereas it seemed like

the velocity profile in simulations C2 was mirrored which suggests that the asymmetry is connected to circumstances in or in front of the inlet. The width of the horizontal air speed profile at $x=0.5$ m was well predicted with the geometrical models of inlet (C2 and D2), but under predicted if simple openings (A2, A4 and B2) were used.

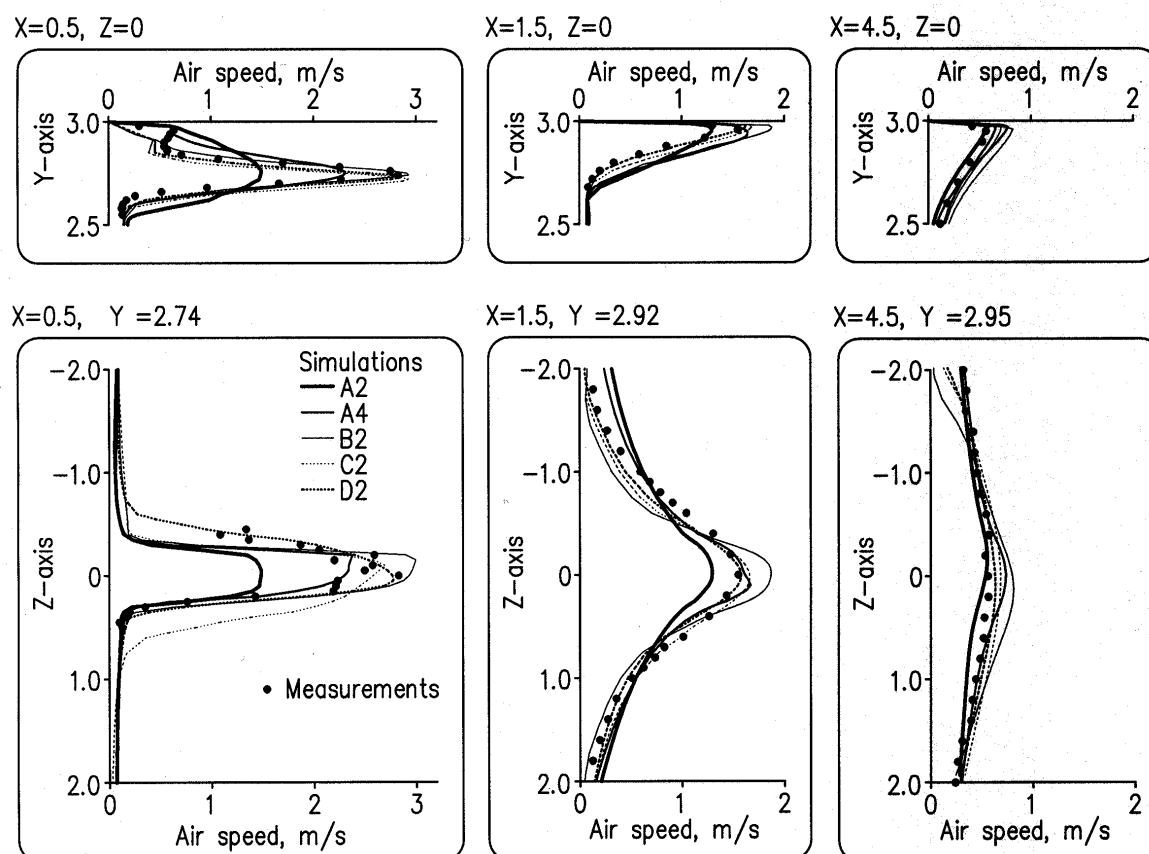


Fig. 7: Air speed profiles beneath the ceiling. Simulation A2, A4, B2, C2 and D2 compared with measurements. Dimensions in metres.

Figure 8 compares measured and simulated air velocity in the occupied zone (0.2 m above the floor). At most of the monitored points there was a good agreement between measurements and simulations and in addition there were only small differences between different simulations. Figure 8 also shows that the velocity decrease along the floor at $z=0$ m was more significant in measurement than in simulation. Especially the simulation with orthogonal grid over predicts the air velocity close to the inlet wall. This is similar to the results of earlier investigations (eg Bjerg et al., 1999; Svidt, 1994), but it is not clear why the simulations with grids parallel to the inlet is closer to the measurements in this part of the room. At $x=6$ m and $z=1, 2$ m or 3 m there was some disagreement on the simulated flow direction, however, the velocity magnitude was at the same level as measured.

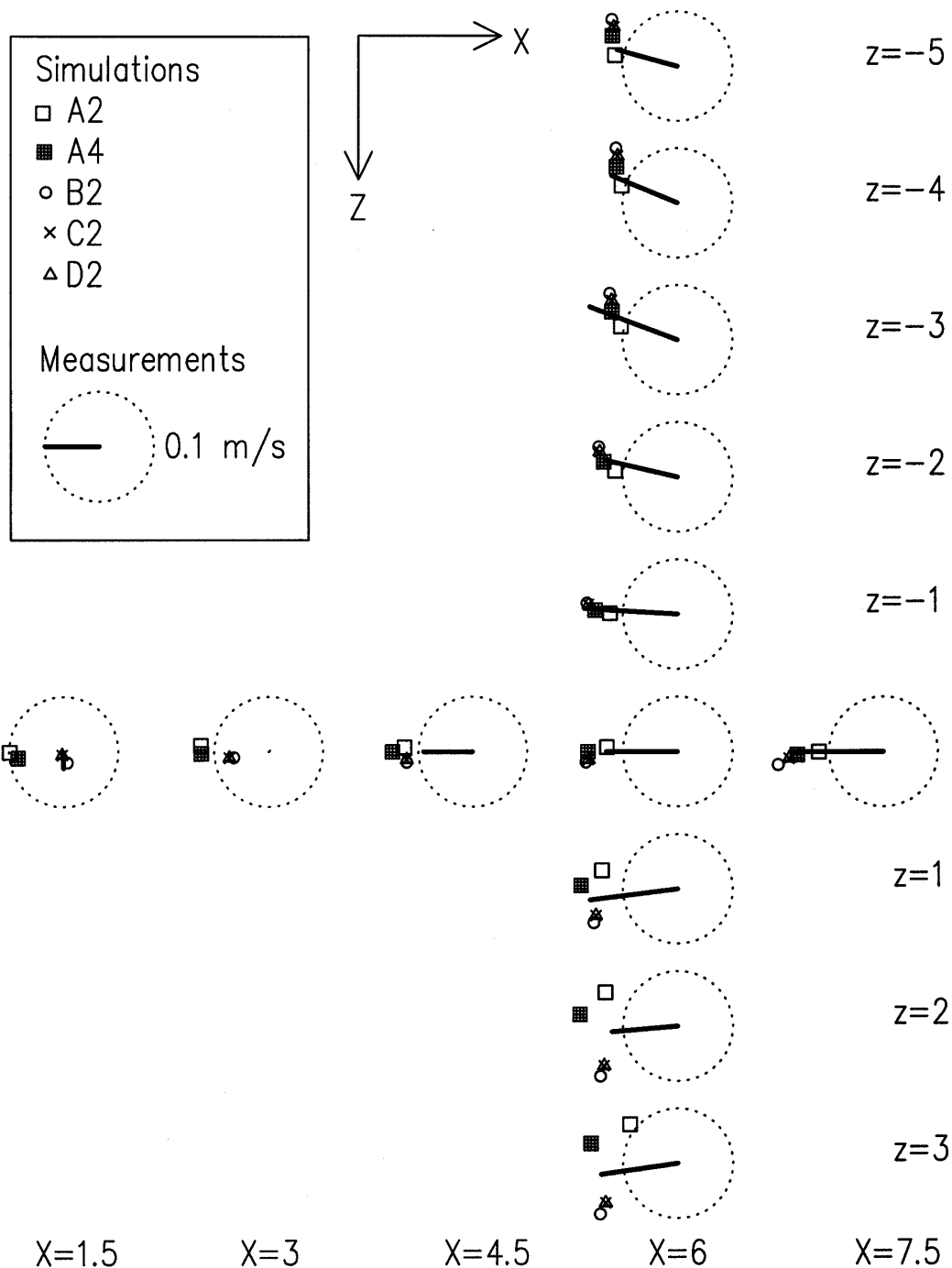


Fig. 8: Comparison of measured and simulated air velocity 0.2 m above floor. Dimensions in metres.

Predictions with the second-order upwind discretization scheme were generally less stable than predictions with the first-order scheme. Lack of stability will probably be a major problem, if the inlets are used in an arrangement where the jet drops from the ceiling before it reach as the end wall and therefore, it is preferable to avoid this method.

Svidt (1994) used the prescribed velocity method to simulate the airflow from a prefabricated wall inlet from another ventilation company. This method implies that the air velocity in a volume in some distance from the inlet is obtained from measurement and implemented as fixed values in the simulation. The strength of this method is that it makes it possible to predict airflow in rooms with geometrically complicated inlets and the method can be applied in coarse and uncomplicated grids. The disadvantages of the method is that it requires intensive measuring data from the inlet and that it might be time consuming to implement the method in the numeric simulation code.

The ongoing development of pre-processors (tools to generate geometry and grid) and the possibilities to interact with CAD-programmes will make it possible to construct geometrical models of more and more complicated inlets. And the corresponding development of computer power and grid refinements methods will makes it possible to handle the required grid distribution in these more and more complicated arrangements.

CONCLUSION

Simulations with geometric models of a prefabricated wall inlet resulted in a good agreement with measurements in the occupied zone and beneath the ceiling of the used test room. Compared with other ways to specify inlet conditions, the method has the great advantage that it requires no velocity measurement data from the inlet. Therefore, it is preferable to use this method, if the complexity of the inlet allows it.

This study was carried out at isothermal conditions, but in real animal houses the airflow are often influenced by temperature differences between inlet air and room air, and consequently, more work is needed to improve numerical predictions of airflow at circumstances where the temperature conditions has a significant influence on the airflow.

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